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New Results from Long-Term Observations of Cyg X-1

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ABSTRACT

Observations of Cyg X-1 between October 1974 and July 1975 reveal a persistent 5.6 day modulation of the 3-6 keV x-ray intensity, having a minimum in phase with superior conjunction of the HDE 226868 binary system. The modulation is found to be most pronounced just prior to the April-May 1975 increase of Cyg X-1, after which both the modulation and intensity are at their lowest values for the entire duration of the observations. These data imply that the x-ray emission from Cyg X-1 arises from the compact member of HDE 226868, and that the increase of April-May 1975 may have represented the depletion of accreting material which had not yet been mixed into a cylindrically symmetric accretion disk about the compact member.

Subject headings: x-ray sources—black holes

I. INTRODUCTION

Cyg X-1 has consistently been associated with x-ray intensity variability on virtually all time scales (c.f. Boldt, et al. 1975). In contrast to its chaotic behavior on timescales $\leq$ 1 sec (c.f. Rothschild, et al. 1974), however, the presently reported data indicate that day-to-day variations in the source are typically within the ~10% statistical uncertainty of the experiment. The relative constancy on this timescale is perturbed only by a persistent 5.6 day modulation in phase with the binary period of HDE 226868. The effect is too large to be sensibly associated with "absorption dips" previously reported, but the coincidence in phase over >30 cycles would appear to dispel any doubts which may remain about the association of Cyg X-1 with HDE 226868.

On longer timescales, the present data yield an apparently monotonic slow increase until the sudden factor-of-three increase of April-May 1975, after which the Cyg X-1 intensity is lower than before. Apparently tracking the Cyg X-1 intensity is the magnitude of the 5.6d modulation. Both of these results can be interpreted as arising from an elevated amount of matter between the binary components prior to the April-May outburst which manifests itself in both an increasing level of emission as the material is accreted onto the secondary, and increased absorption at HDE 226868 superior conjunction.

II. EXPERIMENTAL RESULTS

All of the data reported here are obtained from the Ariel-V All-Sky X-Ray Monitor, a complete description of which may be found in Holt (1975). The experiment is a scanning x-ray pinhole camera which observes most

of the celestial sphere each orbit. The important parameters are a pinhole area of 1 cm^2, an average duty cycle for source observation of $\sim$ 1%, and an efficiency of $\sim$ 60% in the energy range 3-6 keV. The finest temporal resolution of the experiment is one orbit ($\sim$ 100 minutes), and there is no energy resolution available in the data within the 3-6 keV acceptance window.

Figure 1 displays the Cyg X-1 data reported here in daily averages (the gaps are times when the source was out of the useful field of view of the experiment). The increase in the spring of 1975, first reported by Gursky, et al.(1975), commenced on 22 April (Holt, et al., 1975), apparently reached maximum in early May (Heise, et al. 1975), and was well on the way to recovery to the pre-flare state by mid-May (Sanford, et al. 1975). It was out of the field-of-view of this experiment during the decay phase of the flare-up, and when next unambiguously observed in early June 1975 it had apparently returned to its pre-flare low-intensity level.

The same data which were used in the construction of Figure 1 (excluding only the flare-up) were searched for the binary period of HDE 226868 by direct folding of individual measurements taken over no more than 1/2 day. As shown in Figure 2, there is a significant χ^2 deviation from the assumption of source constancy at the HDE 226868 period of 5.60089 days. Important, also, is the observation that the largest contribution to this χ^2 is from the bin centered at superior conjunction of the binary system; the period and phase of HD 226868 used here are from the Copernicus ephemeris (Mason, private communication, 1974).

As a check on the stability of the effect, the data were broken into

$\sim$ 56 day intervals which were each folded at the same period and phase as in Figure 2. These results are displayed in Figure 3, where the bin centered at superior conjunction is always a minimum prior to the increase of April-May 1975, but may not be afterwards. Similarly, the average intensity of the source after May 1975 appears to be less than before. It should be noted that the error bars in all three figures are statistical only, and there are systematic effects (mostly arising from pointing inaccuracies) which are not recoverable. These appear to play no significant role in the 5.6d folds (as evidenced by the lack of a 5.6d component in the Crab Nebula), but could conceivably be important in the interpretation of the gross intensity variation of Figure 3. We estimate that the true error on the four _average_ values in Figure 3 is no larger than the statistical error displayed for each individual bin, as the Crab Nebula is found to be consistent with constancy over the entire interval with a smaller systematic contribution to the error. Figure 3 demonstrates, therefore, that Cyg X-1 exhibited a slowly increasing intensity and 5.6d modulation until the April-May 1975 increase, after which both were significantly lowered. We note that a linear extrapolation of the trend indicated for the data over the interval October 1974 to April 1975 backward in time to October 1973 would imply that the average intensity one year prior to the launch of Ariel 5 could have been lower by a factor of about two, whereas rocket-borne observations (Rothschild et al. 1975) on 4 Oct. 73 and 3 Oct 74 indicate that the 2-40 keV absolute spectrum (averaged over about a minute at a binary phase of 0.17) was invariant to within a limit of about 10% for any likely error in normalization. This suggests that the timescale for the build-up to the April-May 1975 flare is no more than $\sim$ 1/2 year.

III. DISCUSSION

The 5.6 day modulation of the Cyg X-1 intensity cannot be solely attributed to "absorption dips". Such minima have been reported by Mason, et al. (1974) and Li and Clark (1974) with the following "typical" characteristics:

1) a spectral hardening attributable to absorption by cold matter in the line of sight which would amount to no more than a 50% decrease in the 3-6 keV acceptance window of this experiment.
2) a binary phase within $\sim$10% of superior conjunction
3) a duration of $\sim$ 1 hour
4) a probability of occurrence of < 50% at each superior conjunction.

These characteristics imply a <u>maximum</u> overall light curve decrement arising from absorption dips of .002, compared with the .027 $\pm$.004 actually observed in the data displayed in Figure 2 (and .029 $\pm$.005 if only the data prior to the April-June 1975 outburst are used).

Sanford, et al. (1974) have reported a 5.6d modulation of the Cyg X-1 intensity over a single cycle which may be relatable to the present measurements. Although the predominant feature of their light curve is a relative maximum at inferior conjunction, the magnitude of the effect is similar. Utilizing the present prescription of calculating the decrement in the 20% of the binary phase centered at superior conjunction relative to an average for the whole cycle calculated from the remaining 80%, we estimate that the Copernicus "decrement" amounted to $\sim$ 0.05. These authors remarked that this magnitude was not in conflict with the lack of a detectable 5.6d modulation in 35 continuous

days of UHURU observation (Tananbaum et al., 1972). It may be important to note, however, that the UHURU search was performed less than a year after the spring 1971 transition to its low-intensity state, while the Copernicus observation was performed two years after the UHURU study. If the trends in the present data are an indication of what might have happened after the 1971 transition, the 5.6d modulation may have been considerably less than that reported here at the time of the UHURU search.

Mason et al., (1974) have interpreted the absorption dip phenomenon as arising from the core of a stream of cold matter between the two components of the HDE 226868 system which occasionally intercepts the line of sight to Cyg X-1. It is tempting to postulate that the presently reported 5.6d modulation is a lower-level absorption effect. The simplifying assumption of a cosine line-of-sight circumstellar matter distribution centered at superior conjunction yields an average column density in the central bin of Figure 2 of 94% of maximum, while the adjacent bins have a column density of less than 1/3 maximum (there is no absorption contribution to the two outermost bins). Assuming universal abundances in cold matter, Brown and Gould (1970) cross-sections yield a column density of $\sim 2 \times 10^{22}$ H-atoms cm^{-2} in the line-of-sight at superior conjunction. This amount of cold material should have caused a severe reduction in the intensity of x-rays of lower energy than can be measured by this experiment (at least during the time of our observations), but such an effect has not been reported by other investigators. There are several possible resolutions of this apparent inconsistency. Either a high circumstellar temperature ($\gtrsim 10^6$K) or an overabundance of heavy -Z material (sulfur and heavier) may be invoked to reduce the relative absorption

of soft x-rays to hard, but an accretion disk model for Cyg X-1 (c.f. Pringle and Rees, 1972; Shakura and Sunyaev, 1973; Thorne and Price, 1975) may offer a natural explanation. Here the soft x-rays are predominantly produced in the outer, optically thick region of the accretion disk, while the hard component is produced much closer to the accreting black hole (Thorne and Price, 1975, estimate the transition between "soft" and "hard" to be at $\sim$ 2 keV). An increase in the density of the stellar wind to the accretion disk would then have the effect of shadowing the hard emission more efficiently than the soft, and could also yield an increased soft emission owing to a higher accretion rate. Both of these effects would tend to mask any absorption in soft x-rays relative to hard x-rays. Similarly consistent with this qualitative explanation is the slow increase in hard x-ray emission, as the characteristic gas drift time into the hard x-ray-emitting region of the disk is $\geqslant$ 1 month (Thorne and Price, 1975).

IV. SUMMARY

The present data yield an unmistakable association with HDE 226868 which is independent of the interpretation which we have ascribed to the overall variation in intensity and modulation. The χ^2 distribution of Figure 1 does not allow a period which differs by more than 4×10^{-3} of the HDE226868 period of 5.60089d, and the minimum at superior conjunction prior to the April-May 1975 flare-up is similarly suggestive of a firm association.

The interpretation we have given the intensity and modulation variation may not be unique, but is consistent with this and other observations. We suggest that stellar wind pile-up from the HDE 226868 primary, in loading the Cyg X-1 accretion disk, is directly responsible for the two

new effects we are reporting here: the gradually increasing hard x-ray luminosity, and the low-level line-of-sight absorption around superior conjunction.

The increasing x-ray emission may, in turn, increase the radiation pressure to the point where the Lightman and Eardley (1974) instability may trigger the flare-up of April-May 1975. This "high-intensity" state was considerably shorter in duration than that prior to the March-April 1971 "transition", but was typefied by the same high degree of variability on time scales $\sim$ 1 day (c.f. Sanford et al., 1975), in marked contrast to the regular behavior of the source we report here in its low intensity state. The April-May 1975 increase was the only such flare-up observed between October 1974 and July 1975, but may not have been the first since the 1971 transition.

Figure Captions

1. Daily average intensities for Cyg X-1 measured with the ASM, with ±1 sigma statistical errors. The gaps are times when Cyg X-1 is out of the usable field-of-view of the experiment.

2. a) Cyg X-1 and the Crab Nebula folded in 5 bins at the binary period of HDE 226868 with superior conjunction centered in the middle bin. The heavy solid lines are the average source intensities over the whole time interval (which excludes only the flare-up interval from 22 April 1975 to 5 July 1975), and the heavy dashed line in the Cyg X-1 trace is the average of the four bins not including HDE 226868 superior conjunction.

   b) Values of X^2 for the hypothesis of a constant source at the overall average value of Cyg X-1 in trace a) for several trial values of folding period. The data yield a period of 5.605 ±.008d.

3. Cyg X-1 folded with the same period and phase as in Figure 2 in four intervals of ~ 56 days each. The solid heavy lines are average values in each interval, and the <u>total</u> uncertainty in these averages (including aspect as well as statistics) is approximately the same as the statistical error displayed for the individual central bin during the same interval.

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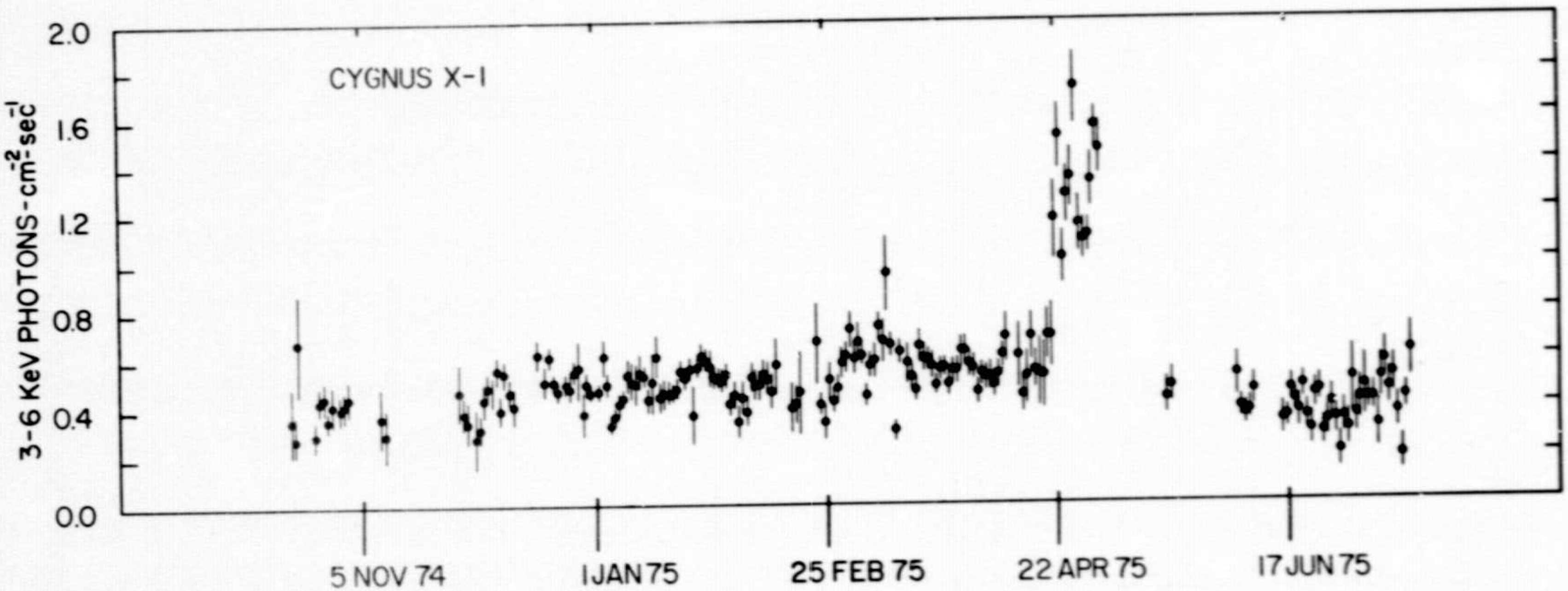
CYGNUS X-1
3-6 KeV PHOTONS-cm^{-2}-sec^{-1}
2.0
1.6
1.2
0.8
0.4
0.0
5 NOV 74
1 JAN 75
25 FEB 75
22 APR 75
17 JUN 75

Fig. 1

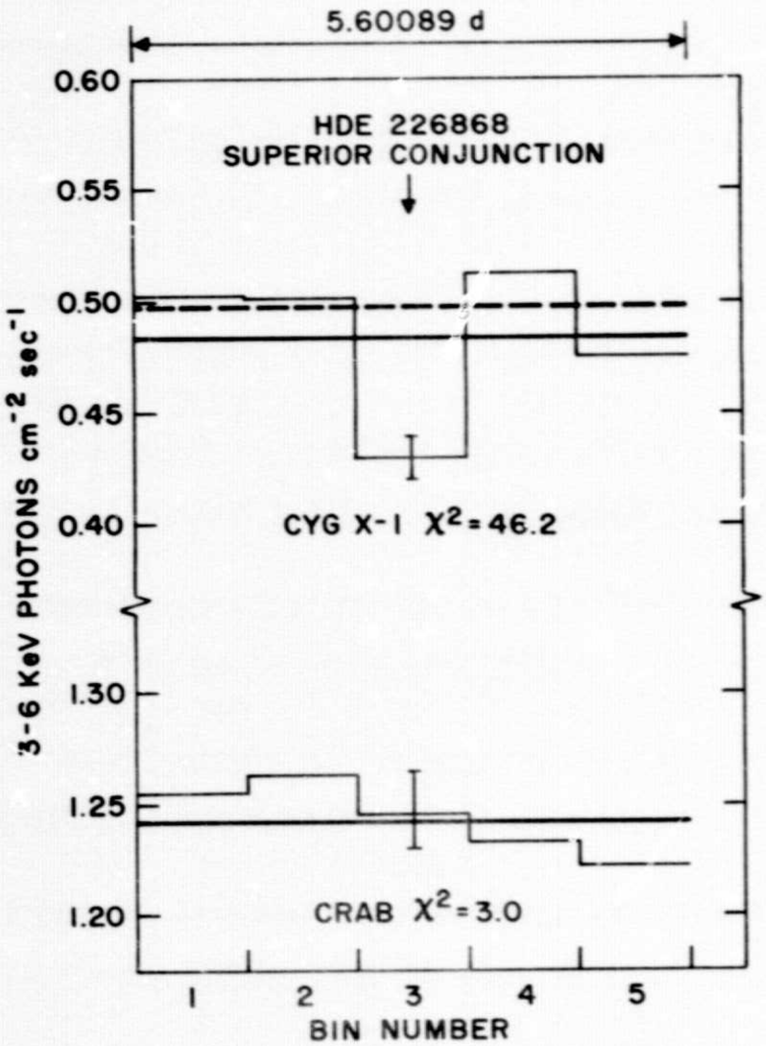
5.60089 d
HDE 226868
SUPERIOR CONJUNCTION
CYG X-1 X^2 = 46.2
CRAB X^2 = 3.0
3-6 KeV PHOTONS cm^{-2} sec^{-1}
0.60
0.55
0.50
0.45
0.40
1.30
1.25
1.20
1
2
3
4
5
BIN NUMBER

Fig. 2a

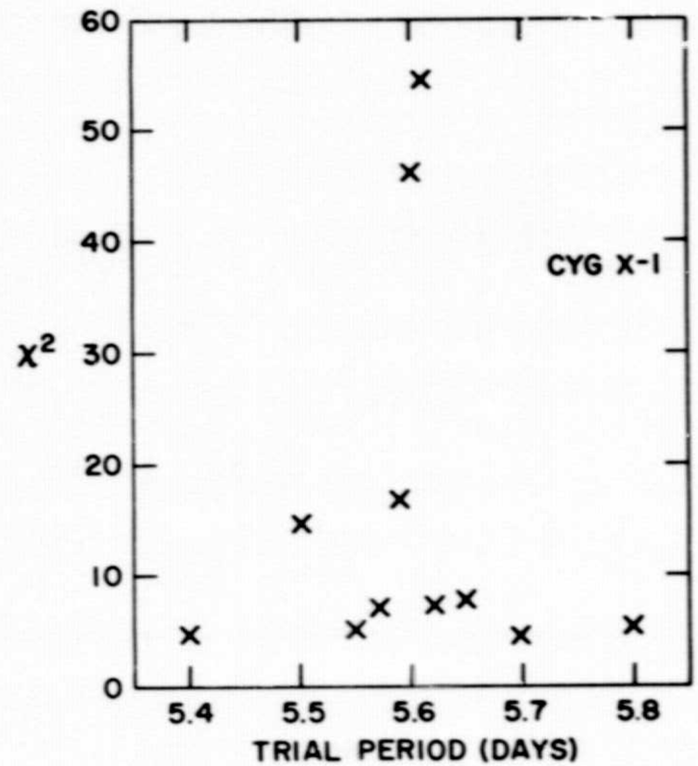
CYG X-1
X^2
60
50
40
30
20
10
0
5.4
5.5
5.6
5.7
5.8
TRIAL PERIOD (DAYS)

Fig. 2b

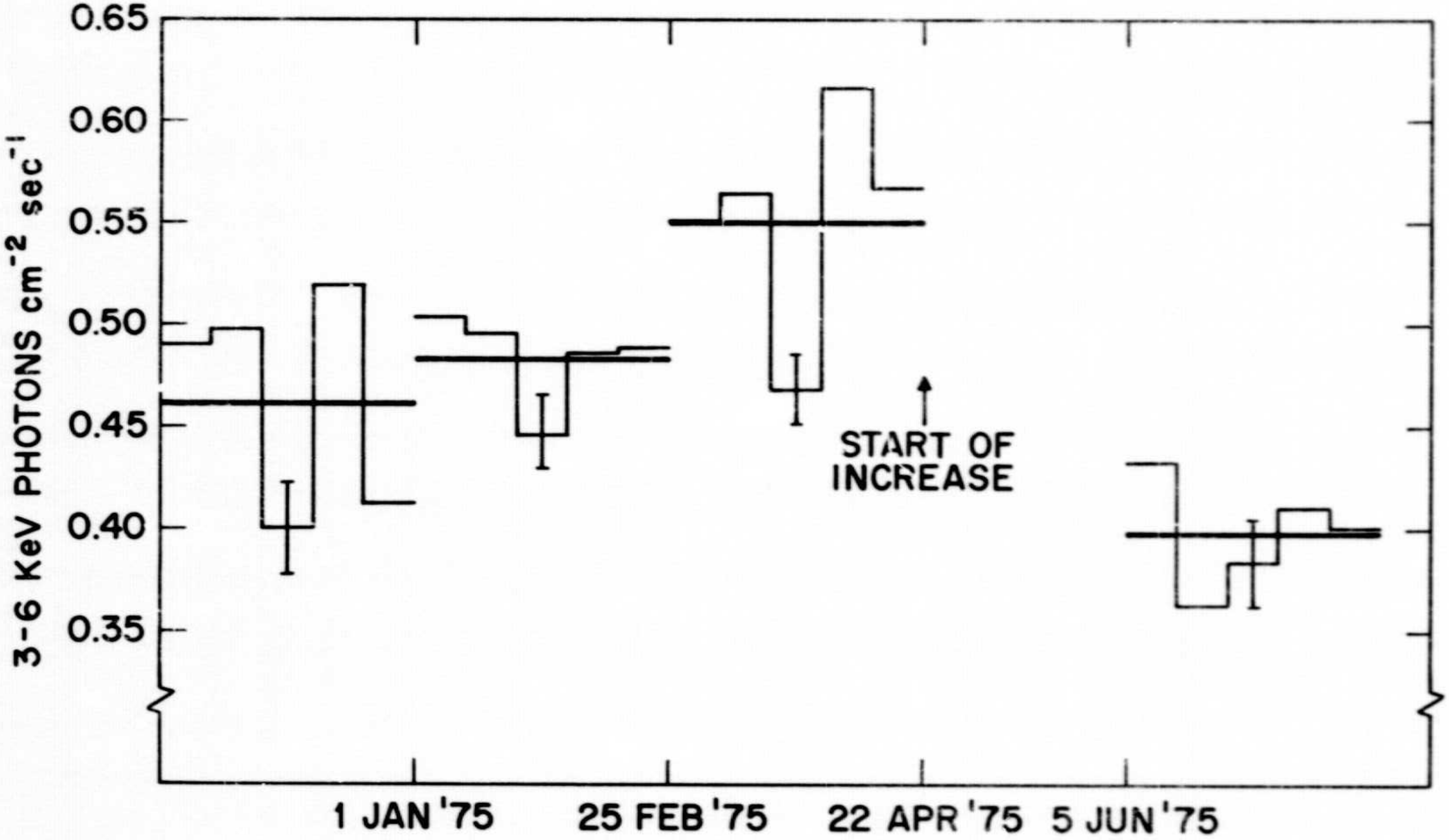
3-6 KeV PHOTONS cm^-2 sec^-1
0.65
0.60
0.55
0.50
0.45
0.40
0.35
START OF
INCREASE
1 JAN '75
25 FEB '75
22 APR '75
5 JUN '75

Fig. 3